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Combat vascular injury: Influence of mechanism of injury on outcome

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ABSTRACT

Background: Haemorrhage is the leading cause of death on the battlefield. Seventy percent of injuries are due to explosive mechanisms. Anecdotally, these patients have had poorer outcomes when compared to those with penetrating mechanisms of injury (MOI). We wished to test the hypothesis that outcomes following vascular reconstruction were worse in blast-injured than non blast-injured patients.
Methods: Retrospective cohort study. British and American combat casualties with arterial injuries sustained in Iraq or Afghanistan (2003–2014) were identified from the UK Joint Theatre Trauma Registry (JTTR). Eligibility included explosive or penetrating MOI, with follow-up to UK hospital discharge, or death. Outcomes were mortality, amputation, graft thrombosis, haemorrhage, and infection. Statistical analysis was performed using Pearson Chi-Square test, t-tests, ANOVA or non-parametric equivalent, and survival analyses.
Results: One hundred and fifteen patients were included, 80 injured by explosive and 35 by penetrating mechanisms. Evacuation time, ISS, number of arterial injuries, age and gender were comparable between groups. Seventy percent of arterial injuries resulted from an explosive MOI. The explosive injuries group received more blood products ($p = 0.008$) and suffered more regions injured ($p < 0.0001$). Early surgical interventions in both were ligation ($n = 36$, 31%), vein graft ($n = 33$, 29%) and shunting ($n = 9$, 8%). Mortality ($n = 12$, 10%) was similar between groups. Differences in limb salvage rates following explosive ($n = 17$, 53%) *vs* penetrating ($n = 13$, 76.47%) mechanisms approached statistical significance ($p = 0.056$). Nine (28%) vein grafted patients developed complications. No evidence of a difference in the incidence of vein graft thrombosis was found when comparing explosive with non-explosive cohorts ($p = 0.154$).
Conclusions: The recorded numbers of vein grafts following combat arterial trauma in are small in the JTTR. No statistically-significant differences in complications, including vein graft thrombosis, were found between cohorts injured by explosive and non-explosive mechanisms.

Background

Each year, more than five million people worldwide die as a result of injury [1], and this number is increasing. Within the United Kingdom injury continues to be the leading cause of death in adults under 45 years of age [2–4], despite a 63% improvement between 2008 and 2015 in the odds of surviving major trauma. The burden of trauma, measured in disability adjusted life years (DALYs) rose 34% between 1990 and 2010 and is conjectured to continue rising [5]. Although civilian injuries are generally attributable to blunt mechanisms [6], explosions involving multiple casualties such as those seen in Boston in 2013 [7] Paris in 2015 [8] and Manchester in 2017, demonstrates the importance of apt blast injury management. Worldwide, terrorist incidents have increased eight fold between 2000 and 2014, the majority being associated with explosive mechanisms [9].

In the context of combat related trauma, haemorrhage has been reported to be the leading cause of death in UK and USA troops [10–12], and 90% of deaths of potential survivors [13]. Explosive mechanisms are implicated in 70% of combat injuries [14], and 63% of lower extremity injuries are associated with explosive devices

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[15]. The prevalence of wartime arterial injury has been reported to be 4.4–7.1% [16–20]. An analysis of the US Department of Defense Trauma Registry (DoDTR) between 2002 and 2009 concluded that the rate of vascular injury was five times higher in Operation Enduring Freedom and Operation Iraqi Freedom than during previous conflicts [21], demonstrating the evolving nature of combat injury mechanisms. During this time, patients with arterial injuries were more likely to survive within the deployed coalition military trauma system than in a civilian environment within the United States. Based on cohorts matched for age, elevated Injury Severity, and arrival hypotension, overall mortality was 4.2% in the former versus 12.6% in the civilian setting, p = 0.006) [22].

Patients with vascular injuries are likely to require damage control resuscitation (DCR), by controlling catastrophic haemorrhage within a <C>ABC algorithm, and employing permissive hypotension with the use of blood products over other fluids [23] [24]. Damage control surgery (DCS) is a facet of the resuscitation sequence and involves expedient control of haemorrhage and contamination, physiological recovery (usually in the intensive care environment) and planned return to the operating theatre. Vascular DCS involves proximal and distal control of the injured vessel and expedient management of the injured site to restore distal perfusion where appropriate. Adjuncts such as Temporary Intra-Vascular Shunts (TIVS) may be useful to temporarily restore perfusion. Within the context of the relatively rich resource available within a Role 3 (R3) medical treatment facility in Afghanistan, this sequence was shortened and the physiological recovery phase could be brought in to the operating theatre, prolonging possible operative intervention and definitive restoration of distal perfusion.

Despite the high standard of care for combat casualties with arterial pathology, those injured by explosive mechanisms have been reported to fare poorly compared to those with penetrating injuries when matched for injury severity, and are more likely to develop and die from coagulopathy and multi-organ failure (MOF) [25]. It is not clear why these differences exist. Likewise, anecdotal evidence suggests that arterial repairs were more likely to thrombose in patients who have sustained their injuries through explosive rather than penetrating mechanisms alone. However, is this true or a reflection of a more severely injured patient? This study sought to answer the final query.

We studied outcomes in blast versus non-blast injured service members to define and characterise the natural history of vascular injury. We hypothesise that repair of vascular injuries following injury by explosive mechanisms have a higher frequency of complications than repair of vascular injuries following penetrating mechanisms of injury.

Methods

The study was designed as a retrospective cohort analysis of a centrally maintained defence database (United Kingdom Joint Theatre Trauma Registry (UK JTTR)). The UK JTTR contains patient demographics (age, gender, nationality), type of injuries (coded, free text, injury scores), drugs including blood products given, parameters (HR, BP, SpO2), type of surgical intervention, the timing of key events, and patient outcomes.

The study setting was Iraq and Afghanistan conflicts (complete dataset (2003–2014)). An audit was registered with the Royal Centre for Defence Medicine (RCDM), Clinical Exploitation Team (RN 140908). A UK JTTR search was performed for 'vascular arterial injuries'. Results were exported and hand searched to ensure that all those who met eligibility criteria were grouped and the remainder removed.

The eligibility criteria were all UK or USA patients who were injured by blast or penetrating mechanisms and underwent a surgical intervention relating to their vascular injury, with follow-up to death or Role 4 (home nation hospital (R4)) discharge. Those with an unrecordable R3 BP or HR, expected to not survive due to head injury (HI AIS = 6) or did not have follow up to hospital (R4) discharge or death were excluded. The most proximal vessel injured was defined as the injured vessel for the purpose of analysis. Blood products were defined as the total of packed red cells, platelets, and fresh frozen plasma units given. Primary and secondary interventions were defined as the first and any subsequent vascular intervention respectively.

Unless otherwise stated, analyses were performed on a complete dataset. Missing data was specified (and excluded from analyses). All data parameters were recorded in real time; interventions were inferred from free text surgical notes; all participants were reported upon in the same way. Data was assessed for normality by distribution, then parametric or non-parametric tests were utilised. Continuous variables were analysed using T-tests / ANOVA if parametric or Mann-Whitney U / Kruskal-Wallis if not. Categorical variables were grouped where necessary and analysed using Pearson Chi-Square test (or Fisher's exact test where more than 20% of the values have expected frequencies less than 5%). Post-hoc Bonferroni corrections were performed in conjunction with multiple testing. Survival analysis was performed on data uncensored for hospital discharge by generating Kaplan-Meier plots, performing a log rank test and generating a hazard ratio (Cox's). Sensitivity analyses were not performed, percentages are expressed as integers.

Data analysis was performed using IBM SPSS Statistics for Windows, Version 22.0. Armonk, NY: IBM Corp. Additional graphs were constructed using GraphPad Prism version 5 for Windows, GraphPad Software, La Jolla, California, USA.

Results

Of 992 casualties who sustained a vascular injury during Operation Herrick, 115 met eligibility criteria (Fig. 1). Eighty of these 115 (70%) sustained blast as the principle mechanism of wounding. The mean age was 25 years (n = 114), one patient was female and two patients were USA nationals. The remainder were UK combat casualties. The median length of follow-up was 34 days following injury (IQR 16.25–96.75). 82% (n = 94) of injuries were located in the extremities, 32% (n = 37) of the total being distal to the popliteal or brachial artery (Fig. 2). There were no differences in the anatomical distribution of arterial injuries between blast and GSW mechanism groups (p = 0.828). Likewise, there were no differences between groups in time from point of wounding (POW) to arrival in ED (n = 94), ISS, or those with an AIS > 3. The mean number of arterial injuries sustained was 1.31 (SD 0.57) overall, with no differences between blast and GSW groups. Patients in the blast group received more blood products (14.0 (8.0-27.5)(8.0–27.5) vs 5.0 (4.0–12.0) (median (IQR), n = 80) respectively (Mann Whitney U p = 0.008)) and had more body regions injured (median and IQR 3.0 (2.0–4.5) and 1.0 (1.0–2.0) respectively (Mann Whitney U p < 0.0001)) (Table 1).

Overall, 11% (n = 13) underwent a primary repair with no statistically significant difference between the groups. In contrast LSV grafts were employed to restore flow in 35% (n = 28) of blast-injured compared to 14% (n = 5) of GSW-injured arteries (p = 0.024, Pearson Chi-Square test). In the series no prosthetic (Polytetrafluoroethylene (PTFE)) graft repairs were performed, and PTFE use was only described in the context of fashioning a patch repair in one patient. This patient was injured by explosive mechanisms and the repair was complicated by thrombosis. The types of surgical intervention performed are reported in Table 2. Of the 115 patients, in only nine (8%) were the use of TIVS reported. These were sited in the Brachial (2), Iliac (1), Femoral (4) and Popliteal (2) arteries. The

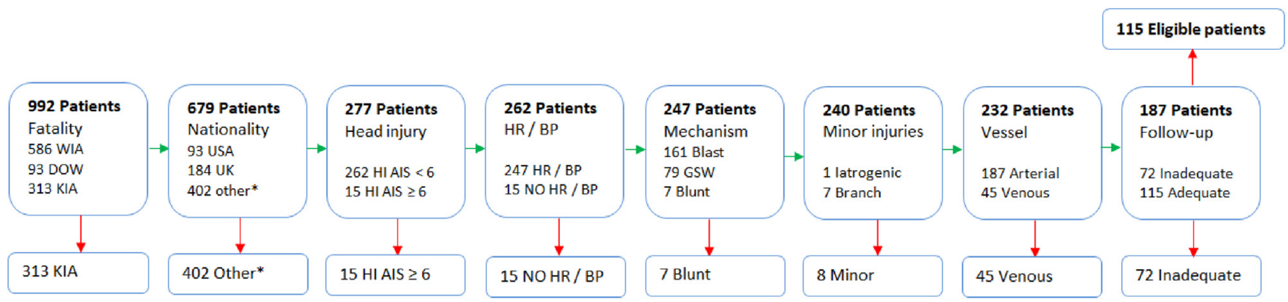

Fig. 1. Patient selection criteria.
Vascular patients identified from within the UK JTTR database from Operations Telic and Herrick. 992 patients sustained a vascular injury, 115 met eligibility criteria. *any patient not UK or USA military. WIA – wounded in action, DOW – died of wounds, KIA – killed in action, UK – United Kingdom, USA – United States of America, HI – head injury, AIS - abbreviated injury scale, HR – heart rate, BP – blood pressure, GSW – gunshot wounds (penetrating mechanism of injury).

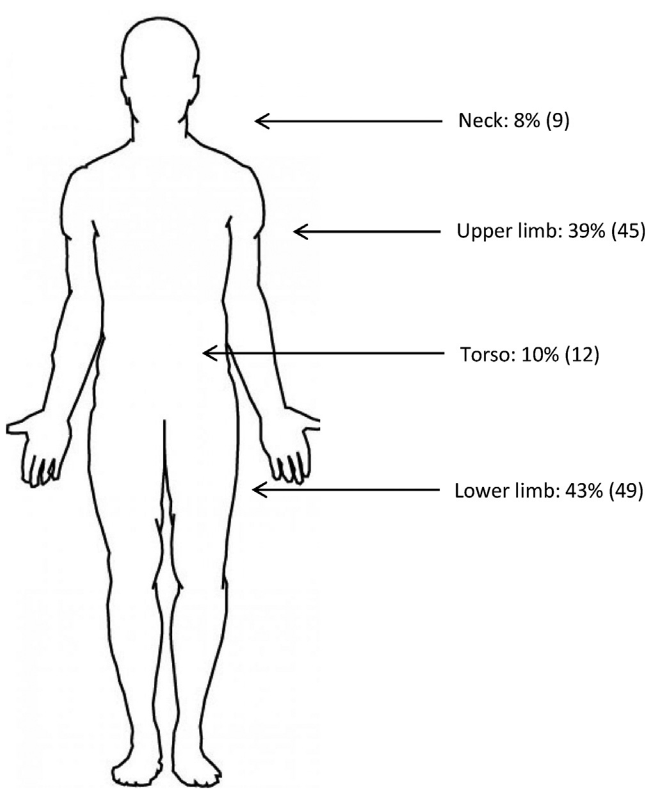

Fig. 2. Arterial wounding pattern of the 115 eligible patients from the UK JTTR. Extremity arterial injured accounted for 82% (94) of all arterial injuries.

Table 1
Baseline characteristics of the study population by mechanism of injury.

Characteristic	Blast (80)	GSW (35)	P value
Minutes from POW to ED[a]	51.0 (40.0–82.5)	54.0 (38.0–71.0)	0.659
ISS[a]	20.0 (12.3–33.0)	16.0 (9.0–25.0)	0.053
AIS >3[b]	8%	0	0.214[c]
Head	1%	0	1.0[c]
Face	10%	6%	0.724[c]
Neck	14%	11%	0.992[c]
Thorax	9%	19%	0.270
Abdominal	1%	6%	0.438[c]
Spine	34%	26%	0.524
Upper Extremity	55%	43%	0.319
Lower Extremity			
Blood products[a]	14.0 (8.0–27.5)	5.0 (4.0–12.0)	0.008
Number of regions injured^	3.0 (2.0–4.5)	1.0 (1.0–2.0)	<0.0001
Distribution of injury[d]	Extremity	Extremity	0.828
Number of arterial injuries[a]	1.0 (1.0–1.75)	1.0 (1.0–2.0)	0.865

POW – point of wounding, ED – emergency department, ISS – injury severity score, AIS - abbreviated injury scale, GSW – gunshot wound (penetrating).
[a] Median (IQR).
[b] Percentage (%).
[c] Fisher's exact test.
[d] Mode.

overall mean TIVS duration was 29 h (range 8–62 hours). Of the seven lower limb TIVS five limbs were initially salvaged and two required a secondary amputation as they were unsalvageable.

Overall, 28% (n = 22) and 29% (n = 10) patients in the blast and GSW groups respectively suffered a complication following arterial intervention (p = 1.0) (Fig. 3, Table 3). When non-restorative interventions (ligation (36), exploration alone [3], proximal amputation (6)) and those who had poorly reported interventions [7] or had died (4)) were removed, 59 restorative repairs remained, 70% (n = 41) of which were performed in the blast group. Of these repairs 37% (n = 15 of 41) and 28% (n = 5 of 18) of patients in the blast and GSW group respectively experienced a complication (p = 0.57), all early graft or TIVS occlusions (10%, n = 6) occurred in the blast group (15%, 6 of 41, p = 0.10).

Overall in the 115 patients complications occurred in 28% (n = 32) and mortality was 10% (n = 12), with no differences between groups. 82% (n = 9) of deaths occurred in the first week after injury. Of the 59 patients with restorative repairs only two (3%) died. Thrombosis was reported in 17% (n = 10) overall, 22% (9 of 41) blast versus 6% (1 of 18) of the GSW group, RR = 3.94, p = 0.154), and 7% (n = 8) overall developed a wound infection. Lower limb injuries formed 43% (n = 49) of the series, 35% (n = 17) due to penetrating and 65.3% (n = 32) due to blast mechanisms of injury respectively. Limb salvage in this group was 61% (n = 30) overall, with 77% (n = 13) of limbs salvaged in the GSW group

Table 2
Nature of arterial repairs by mechanism of injury. Figures given as percentage (absolute number).

Primary surgical intervention	Blast (80)	GSW (35)
LSV graft	35 (28)	14 (5)
Shunt	5 (4)	14 (5)
Ligation	30 (24)	34 (12)
Primary repair	10 (8)	14 (5)
Patch* repair	1 (1)[a]	9 (3)[b]
Exploration only	1 (1)	6 (2)
Died on the table	1 (1)	9 (3)
Proximal amputation	8 (6)	0
Unknown	9 (7)	0

There were no statistically significant differences between groups. (GSW - gunshot wound, LSV – long saphenous vein, PTFE – polytetrafluoroethylene).
[a] PTFE patch.
[b] Vein patch.

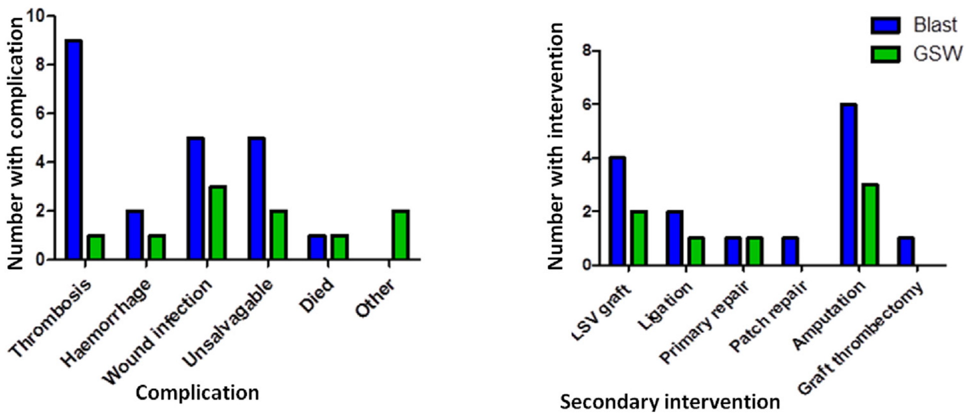

Fig. 3. Left - Primary complications of arterial repair by mechanism of injury and Right - Secondary arterial procedures performed following complications.

Table 3
Primary complication following arterial intervention by MOI (percentage (number)).

Primary complication (N = 115)	Total 28% (N = 32)	Blast 28% (N = 22)	GSW 29% (N = 10)
Thrombosis	31 (10)	41 (9)	10 (1)
Haemorrhage	9(3)	9 (2)	10 (1)
Wound infection	25 (8)	23 (5)	30 (3)
Unsalvageable limb	22 (7)	23 (5)	20 (2)
Died	6 (2)	5 (1)	10 (1)
Missed intimal injury	3 (1)	0	10 (1)
Compartment necrosis	3 (1)	0	10 (1)

There were no statistically significant differences between groups.

compared to 53% (n = 17) in the blast group (p = 0.056). Those with a restorative arterial repair had a re-intervention rate of 25% (n = 15), 27% (n = 11) of which occurred in the blast group (p = 1.0). The reinterventions performed were LSV grafting (n = 6), amputation (n = 3), vessel ligation (n = 2), primary or patch repair (n = 2), and LSV graft thrombectomy (n = 1).

An analysis of thrombosis (Fig. 4) between blast and GSW groups revealed that 25% (8 of 32) of patients who have a blast mechanism implicated develop a LSV or TIVS thrombosis, compared with 0 (0 of 10) in the GSW group (p = 0.165). When analysed for all restorative arterial interventions for the duration of follow-up 22% (n = 9 of 41) of those in the blast group and 6% (n = 1

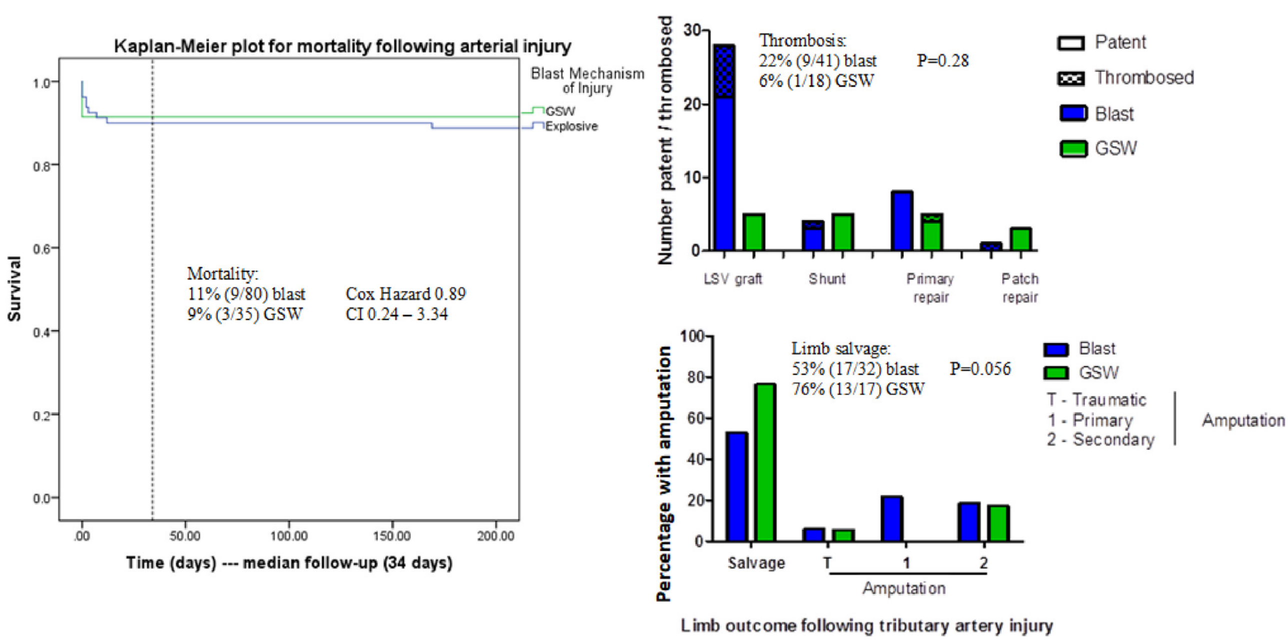

Fig. 4. – Patient outcomes. Mortality (Kaplan-Meier), thrombosis and limb salvage by mechanism of injury. Overall complications occurred in 28% (n = 32): Mortality (10%, n = 12), thrombosis (9%, n = 10) and wound infection (7%, n = 8). 43% (49 of 115) had lower limb arterial injuries, 65% (n = 32) were caused by blast. Limb salvage was 74%, and there were no statistical differences between groups.

of 18) of those in the GSW group developed a thrombosis (p = 0.154) (18% overall). There is no evidence in this cohort to suggest that the blast injured were more likely to thrombose than the non-blast injured.

Discussion

In this cohort of blast and GSW patients with vascular injury, we found no differences between the overall number of complications in explosive and penetrating mechanism groups. Differences in limb amputation frequency between groups approached significance (p = 0.056). Although thrombosis developed in 25% of the venous conduits or TIVS of patients in this cohort exposed to blast overall, and 22% in the blast group of those who underwent initial restorative arterial intervention compared to none and 6% respectively those patients injured by penetrating mechanisms, these results were not statistically significant.

Explosive devices transmit energy and injure through a number of mechanisms, a shock wave interface which is implicated in the rupture of hollow visci, concurrent fragmentation wounding from the device or surroundings, displacement and burn or inhalation injury. Injuries induced by explosive mechanisms may be more severe than those caused by penetrating means despite similar ISS scores as reflected by increased blood product usage and more body region AIS scores. This may be due to a lower score in multiple regions combined with a vagally mediated physiological response to blast injury [26]. It may also be linked in part by the association between blast injuries and amputations, and explains the greater amount of blood products received by those injured by blast compared to GSW.

This study reports the majority of arterial injuries to be in the extremities, as in other series [16,17,19,27]. Arteries were mostly ligated (31%) or had a LSV interposition graft sited (29%) as the primary procedure in this series. This is largely in keeping with published ligation rates of 18.90–32.08% [17,19,28]. As the severity of trauma (AIS, ISS) increases with time [29], it is important to keep in mind that ligation may represent an essential, life-saving bridge to amputation of an unsalvageable limb. TIVS were used in only 8% of all arterial injuries in this series. This figure is, however, comparable to other series which have reported their use in 0% [27] to 17% of cases [17].

Thrombosis rates are incompletely reported in many studies, which rely on harder end-points such as amputation and mortality to judge the success of outcomes. However, a thrombosis rate of 4.5% has been reported in interposition grafts following repair for all cause trauma [16]. Although not reported in this series, the laterality of the donor vein relative to the injured artery in autologous vein repairs may have a bearing on the development of thrombosis as ipsilateral or proximal veins may have altered intimal characteristics compared to remote vein. Our own finding of an overall thrombosis rate of 18% of those with a restorative arterial procedure is relatively high, which may be a reflection of a higher proportion of patients injured by explosive means. Also, in this war injured cohort the severity and degree of global injury is likely to be greater.

Perioperative mortality was 2% in this series (rising to 8% at seven days) in keeping with others 1.3%–6% [16,17,28], likewise 19 amputations were performed, (17% of the cohort overall) similarly to others (6.6–16% [17,19]. There were no differences in either outcome when considered by mechanism. This lack of difference may be due to the low number of amputations in the cohort, as a report of consecutive casualties between January 2007 and December 2010 demonstrated that a quarter of the 656 combat casualties who sustained IED injuries died and 169 sustained 278 lower limb amputations [30].

A contemporary evaluation of the diagnosis, management and outcomes of 542 civilians with arterial and venous injuries in 14 centres in the USA [31] reported that 50.9% underwent non-operative management and overall 11.3%, 6.8%, 5.7% and 2.6% underwent LSV grafting (or equivalent), primary repair, ligation and TIVS respectively compared with 29%, 11%, 31% and 8% in this study. The differences in ligation and shunting may be due to differences in wounding pattern, there being fewer extremity injuries seen in the civilian group compared to the military (26% versus 43%). This is turn is likely to be due to wounding mechanism, the explosive component being 70% in this combat series compared to 47% blunt, and 36.5% penetrating mechanisms reported by the civilian group. A direct comparison of outcomes between studies would be flawed due to these differences. Mortality however was similar (12.7% and 9.6%), and other complications of amputation and thrombosis were not reported by the civilian study investigators.

115 patients were included in the study, well in keeping with the other published series relating to war-time vascular injuries. However subgroup lower extremity vascular trauma analyses did not establish significant differences between groups despite including all possible candidates. This was firstly because of a lack of comprehensive follow-up data of USA service personnel in the UK JTTR database leading to their almost complete exclusion from the study, and secondly, as a consequence, the reduced power needed to identify true differences between the blast and penetrating subgroups. Only two USA casualties were included in this study, data from the remainder was recorded within the USA trauma registry and not the UK JTTR. By design the study was representative, real outcomes have been measured. This is also a limitation however, as groups in the series received differing numbers of blood products, the ISS was higher. A further limitation was the poverty of reporting of heparin and tranexamic acid, which may potentially have a bearing on the development of thrombosis in general, or the patency and outcomes of TIVS if given differentially between groups. Whilst tranexamic acid administration is a variable captured by the UK JTTR this data was not recorded, and therefore not available for analysis. Unfortunately it was not possible to review the functional outcomes of patients in this study.

Over the course of the time studied (2003–2014) the standard of care delivered may have varied, suggested by the finding that despite significant increases in mean injury severity scores during operations in Afghanistan the level and number of lower extremity amputations [22] remained unchanged [11,25]. Likewise a 50% chance of survival was associated with a steadily increasing New Injury Severity Score (NISS) from 32 in 2003 to 60 in 2012 [23].

It must be considered that males in their twenties formed the overwhelming majority of the patients in this study; such is the nature of undertaking a study of combat casualties. As such this has unequivocal relevance to the military population, and is largely relevant to the UK trauma population, the majority of whom being male and under forty [32]. However these findings may not apply to those who are at the extremes of age, have comorbidities or are taking medications.

In summary over 80% of the combat arterial injuries sustained by UK and USA service personnel with follow-up to discharge between 2003 and 2014 were in an extremity. Over 70% of injuries were as a result of a blast mechanism and those in the explosive group received more blood products and had more regions injured. No significant differences in overall blast and GSW complications were found. The thrombosis rate was three times higher and amputation rates two times higher in the blast group but neither were statistically significantly different. Combining these data with similar datasets amongst coalition patients may allow us to understand better any influence of blast on outcomes following vascular trauma.

Conflicts of interest

No authors have financial or personal relationships with other people or organisations that could inappropriately influence (bias) their work. This includes employment, consultancies, stock ownership, honoraria, paid expert testimony, patent applications/registrations, and grants or other funding.

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